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REPORT

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DIGITAL TELEVISION ROUTING SYSTEMS: AN EXPERIMENTAL OPTICAL SWITCHING MATRIX

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Summary

A mechanical-optical switching matrix has been built as part of a study into the distribution of digital video signals within a television studio centre. The matrix is based on a 10-by-10 arrangement, of which two sections, one 4-by-4 and the other, 1-by-10, have been populated. Details of the construction and operation of the matrix are given. The matrix performs reliably; its performance indicates that in principle the design could be extended to realise a 30-by-30 matrix.

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1. Introduction

Optical fibre transmission is being considered for digital interconnections in television studio centres. The main advantages of optical fibre over coaxial cable are its greater range and bandwidth. Other significant advantages are the absence of cross-talk and interference, the elimination of equalisers, the absence of hum and earthing problems, and the possibility of smaller, lighter cables. Equipment has been designed and built by the BBC to demonstrate the transmission of a television signal in digital form over a multimode optical fibre link.[1] This equipment uses a transmitter based on a semiconductor laser diode. It was seen that the large power margin inherent in a short laser-based link would allow optical switching and distribution.

In a television studio centre it must be possible to switch and distribute signals, to permit the routing of sources to destinations, and for monitoring and maintenance. A method of switching the optical signals themselves is desirable because it is expensive to convert the signals back to electrical form for this purpose. The requirements for a studio routing network are discussed in detail in another Report,[2] together with a general review of optical switching techniques. Most methods of optical switching fall into one of two classes, those that use mechanical techniques and those that use some form of solid-state interaction (integrated optics). Integrated optical switching is reviewed in more detail in a separate Report.[3]

This Report describes an experimental switching matrix based on mechanical techniques. The matrix is non-blocking, that is, the setting of a path through the matrix does not preclude any other path, except that two inputs may not be routed to the same output. The matrix can route each input to any number of outputs simultaneously, an essential requirement of a studio centre switching matrix. Routing to a number of outputs at once is achieved by dividing the signals with partially-reflecting mirrors. The matrix operates with multimode fibre. Operation with single-mode fibre is possible in principle, but in practice there would be difficulties in meeting the more stringent tolerances.

2. Description of the matrix

The matrix is based on a crosspoint arrangement, and uses a partially-reflecting mirror at each crosspoint to tap the signals. The principle of operation is shown in Fig. 1, and there is a general view of the matrix itself in Fig. 2.

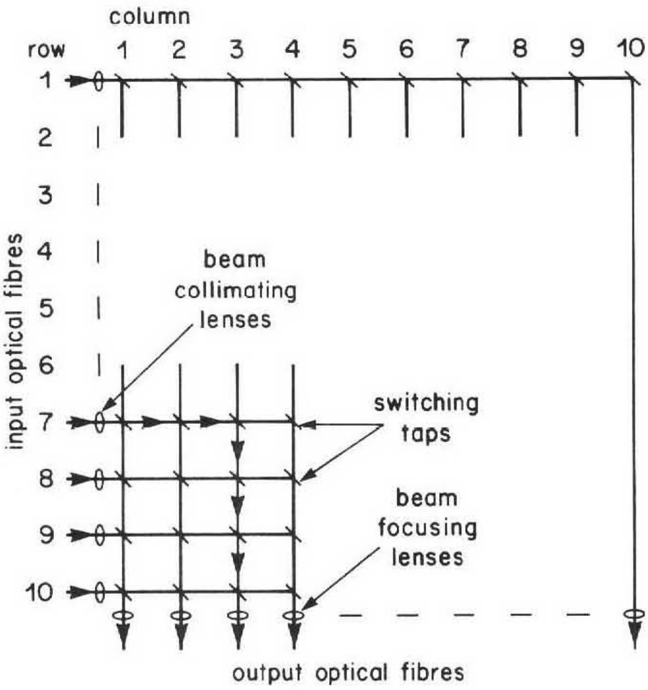

Fig. 1 – Basic arrangement of the matrix.

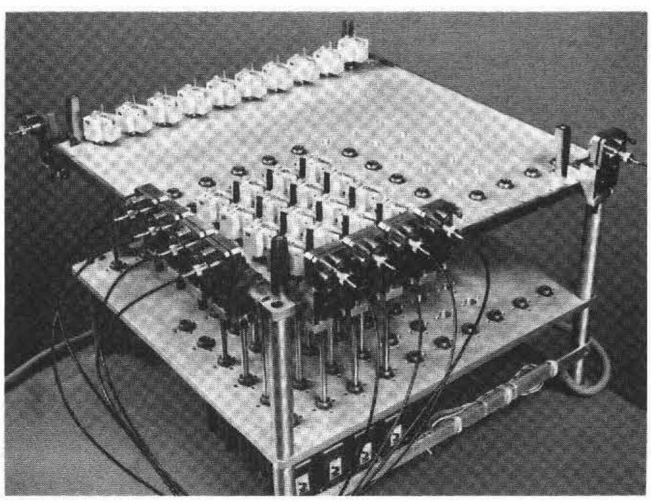

Fig. 2 – The matrix, showing optical fibre connections.

The matrix consists of two populated portions of a 10-by-10 array, one of 4-by-4, and a second, 1-by-10 that includes the longest optical path. This allowed representative measurements to be made without building the entire array.

The incoming and outgoing fibres are arranged along adjacent sides of the matrix. Lenses collimate the light from the fibre ends into a set of parallel beams that traverse the matrix. At each crosspoint there is a mirror assembly that can be moved upwards to intercept the beam and deflect part of it towards an outgoing fibre. The beams are focused onto the ends of the outgoing fibres by a second row of lenses. The mirror assemblies are moved by solenoids actuated by simple relay circuits.

As shown in Fig. 3 each mirror assembly consists of two mirrors, each deflecting the beam by 135 degrees. Thus, any slight rotation of the mirror assembly in its sliding bearing will leave the direction of the deflected beam unchanged, so that it remains trained on the outgoing fibre core. Although there will be a slight lateral displacement of the beam, causing the edge of the beam to miss the fibre core, this effect is relatively small; it was calculated that the double mirror arrangement was only a fiftieth as sensitive as a single mirror would be to rotational errors.

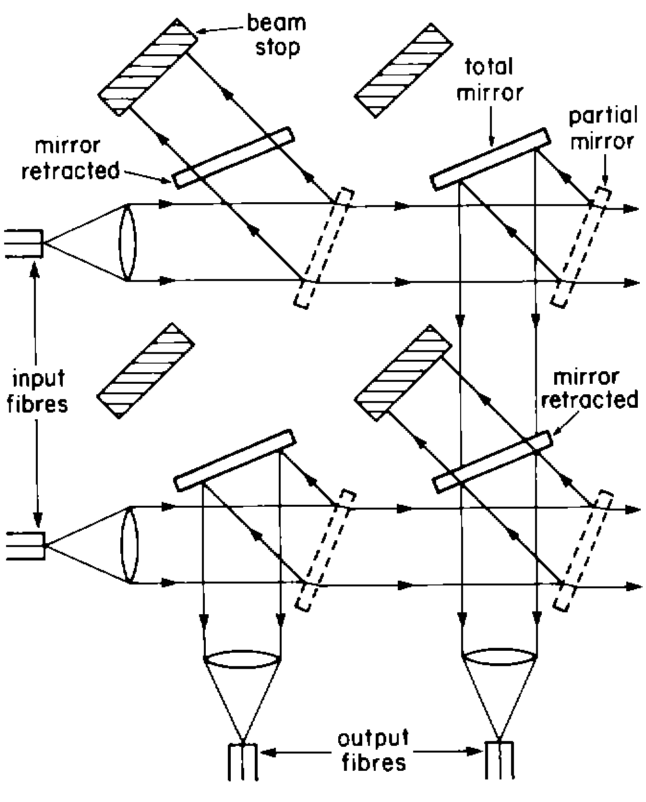

Fig. 3 – Principle of matrix switching.

As may be seen from Fig. 4 the first mirror is partially reflecting, and is tall enough to remain in the beam when the assembly is retracted. The switching is therefore actually done by the second mirror, which is fully reflecting. Arranging the partially-reflecting mirror to remain in the beam avoids the disturbance that would occur as the edge of the mirror passes through the beam, and maintains the power to subsequent stages at a constant level. Also, the small lateral shift imparted to the portion of the beam which passes through the mirror is constant. In a large matrix this lateral shift would build up to several millimetres, comparable with the width of the beam. If the partial mirrors were allowed to drop out of the beam then the change in lateral shift would cause further variations in power.

It can be seen from Fig. 2 that the frame of the matrix consists of two parallel plates, separated by spacers. Each plate contains bearings through which shafts carrying the mirrors slide. Although a single plate would have resulted in a more compact design, calculations showed that the shafts would rock excessively in a single bearing, given that some clearance would be needed to allow the shafts to slide freely. Two bearings were therefore used, separated by 150 mm. It was then possible to use oil-impregnated phosphor-bronze bushes, at a fraction of the cost of linear roller bearings.

The partially-reflecting mirrors are glass, with multiple dielectric coatings. Metal coatings were not used because of their significantly higher loss.

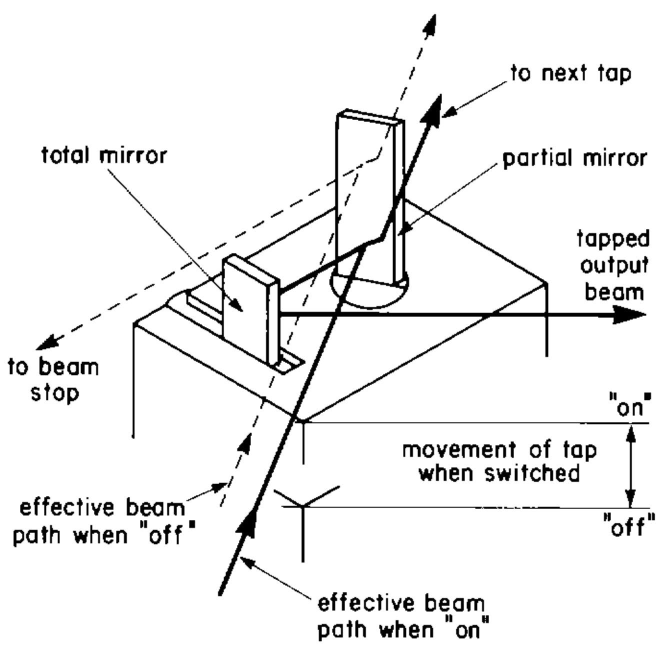

Fig. 4 – View of single tap showing beam switching.

The Appendix gives details of the calculations of mirror reflectance for an even distribution of power between the outputs. Over the first few mirrors in each row, the reflectance varies only a little, and is comparable with the accuracy with which the mirrors could be made. Therefore, common values of reflectance were used for two groups of mirrors in each row. The values chosen make best use of the available power by equalising the power diverted by the last tap in each group. The calculated values, and the values actually used, are listed in Table 1. The calculations were made assuming a transmission efficiency for each mirror of 95%. The use of groups of identical mirrors increases the insertion loss of the matrix by approximately 0.9 dB at the last tap in each group, but reduces the loss elsewhere.

The table gives all the values of the 1-by-10 array. The 4-by-4 array uses just the last four values. The same values can be used in both arrays because of the way in which the mirror reflectance is determined; the last mirror in a row is fully reflecting, this determines the reflectance of the preceeding mirror, and so on.

Position of mirror	Reflectance, % Actual	Calculated
1	10.5	7.9
2	10.5	9.0
3	10.5	10.4
4	10.5	12.2
5	23.1	14.6
6	23.1	18.0
7	23.1	23.2
8	31.6	31.7
9	48.7	49.0
10	100.0	100.0

Table 1 : Reflectances of partial mirrors

The mirrors are adjustable, the partially-reflecting mirrors by rotation about a vertical axis, the fully-reflecting mirrors about a horizontal axis. Adjustment is by finely-threaded screws acting on levers protruding from the shafts to which the mirrors are fixed.

The position of the fibre ends with respect to the collimating and focusing lenses is also adjustable, by means of kinematic mounts that vary focus, azimuth and elevation. It is also possible to adjust the height and lateral position of the lenses themselves. At the inputs this allows a set of collimated beams to be produced that are all at the same height, parallel and equally spaced, so as to be aligned with the mirror system. At the outputs the adjustments are used to focus the light accurately on the fibre cores.

Multimode fibre with a 50 μm core and 125 μm cladding is used. The fibre is terminated with 'Stratos' type 430 connectors. These have accurately machined conical tips that locate the end of the fibre both longitudinally and laterally. The connectors are held in sockets fixed to the kinematic mounts.

Experiments showed that a major cause of optical loss was poor collimation of the beams. Initially rod lenses were used for compactness and ease of focusing; the focal point is designed to be on the rear surface of the lens. However, the difficulty of specifying the focal length at a specific wavelength (semiconductor laser diodes can vary over about 40 nm), and problems with geometrical aberrations led to their abandonment in favour of conventional planoconvex lenses.

The choice of lenses was a compromise between focal length and numerical aperture, given that small lenses were needed to keep the size of the matrix down. The numerical aperture should match that of the fibre, to collect all the light. On the other hand, the focal length should be as long as possible. This is because the core of the fibre is of finite size, so the beam diverges even if the end of the fibre is placed in the focal plane, the divergence being inversely proportional to the focal length of the lens. Oversize lenses were used at the outputs to aid alignment.

The use of single-mode (monomode) fibre would put more stringent requirements on the matrix. The core of single-mode fibre is about six times smaller than telecommunications grade multimode fibre (9 μm against 50 μm). The mirror and lens adjusters are adequate for multimode fibre, but for single-mode fibre it would be necessary to replace them with piezo-electric adjustments. Continuous positional error feedback may also have to be considered to compensate for wear and thermal expansion. Better lenses would be needed to reduce aberrations.

3. Alignment

The matrix was designed for 820 nm, the wavelength of the laser used in the experimental digital television transmission equipment. Initial alignment of the matrix was performed using red light at 633 nm from a Helium-Neon laser, and minor corrections were then made at 820 nm. A visible beam made alignment easier, and the corrections for the change of wavelength were small and limited to the collimating lenses.

The alignment procedure for the 4-by-4 array was as follows:

(i) The lens mounts at the inputs were adjusted with the aid of a template to give horizontal parallel beams of constant cross-section.
(ii) The mirrors in the row furthest from the output ports were adjusted so that the resultant deflection angle was 90 degrees, and also so that the deflected beams were again horizontal.
(iii) The output ports were adjusted to intercept the deflected beams, using their horizontal and vertical motions. The received power was maximised by a fine adjustment of the kinematic mounts.
(iv) The mirror assemblies in the remaining rows were aligned, again by maximising received power.
(v) The Helium-Neon laser was replaced by the semiconductor laser diode from the experimental equipment, and the input and output ports were realigned. Only small adjustments were needed because the focal length of the collimating lenses changes slightly with wavelength.

4. Performance

4.1 Insertion loss

In optical devices where a beam is divided it is customary to distinguish between two types of loss, division loss and excess loss. Division loss is the inevitable result of dividing the beam by a passive component; excess loss represents the light actually lost from the system, for example by absorption, scattering, or vignetting. The division loss in the 1-by-10 section is 10 dB, and in the 4-by-4 section is 6 dB. A statement of the excess loss is more instructive because it represents losses that are in principle avoidable.

Measurements were made with an optical power meter with approximately 180 m of coiled multimode fibre ahead of, and following, the matrix. This avoided spurious readings caused by light travelling for a short distance in the fibre cladding. The power through the input and output fibres when connected together was also measured. This measurement was then subtracted from the first measurements to give the loss in the matrix itself.

The excess losses in the 1-by-10 and 4-by-4 sections are shown in Tables 2 and 3.

Optical losses in the 4-by-4 array were found to be on average 1.8 dB greater than in the 1-by-10 array. This was because a small error in the alignment of a mirror in the 1-by-10 array could be compensated by adjusting the corresponding output lens. In the 4-by-4 array this was not possible because such an adjustment would upset other optical paths. This has implications for large arrays and for monomode fibre, whose core is less than one fifth the diameter of a multimode fibre core. The problems of alignment are discussed further in Section 5.

No temperature dependent effects were found with the matrix in a laboratory. Any residual power fluctuations were less than 0.1 dB, the resolution limit of the power meter.

4.2 Cross-talk

Cross-talk was, as expected, immeasurably low (the measurement was limited to -70 dB by stray light). This is one of the major advantages of using

	Tap column number										
	1	2	3	4	5	6	7	8	9	10	Average
Excess loss (dB)	7.9	9.1	8.2	9.1	6.6	7.8	8.9	7.5	7.7	5.7	7.9

Table 2. : Excess loss in the 1-by-10 paths in the matrix.

		Tap column				
		1	2	3	4	Average
Tap row	1	9.8	9.9	11.5	7.7	
	2	11.4	11.5	11.4	7.1	
	3	12.8	10.9	10.0	8.6	9·7
	4	9.9	9.4	7.9	6.1	

Table 3 : Excess loss (dB) along the sixteen paths in the 4-by-4 section.

free-space optics in an optical switch. It was, however, necessary to fit beam stops; it can be seen from Fig. 3 that the square grid arrangement of the taps causes the deflected beams to lie at precisely the correct angle to be intercepted by other taps on the same diagonal.

5. Reliability and suitability for operational use

The trend in electrical and electronic equipment is to replace moving parts with solid state components. Solid-state devices are supposedly more reliable and need less maintenance. It is therefore reasonable to ask if a return to a mechanical design is desirable.

In fact there is a distinct difference between the mechanically-operated optical switch and a mechanically-operated electrical switch. In the electrical switch the conducting parts themselves are brought into contact. Spring force is used to ensure good contact and a clean break. Failure is usually caused by wear of the contacts or weakening of the springs. In contrast, there is no physical contact in an optical switch; movement is used only to bring the various components into optical alignment.

Nevertheless, if the bearings which guide the shafts suffer wear, the alignment of the mirrors will be upset. An experiment was carried out in which one tap was switched on and off over 25,000 times, equivalent to about 15 years operational use. The optical power was found to vary by no more than 0.1 dB. When dismantled for inspection almost no wear on the shaft was apparent.

The large forces generated by the solenoids are absorbed by rubber end-stops, and all adjustments are provided with locking screws. The ruggedness of the design was demonstrated when the matrix was transported over 50 km by car with no change in alignment being needed.

Dust or contaminants from the air settling on the mirrors would increase loss and ultimately cause cross-talk. In practice this was not found to be a problem. The matrix is protected by a removable cover, which provides adequate protection in the laboratory. Although the cover does not form an air-tight seal, a suitable cover could be provided for operational use.

Alignment is lengthy and critical. The main problem, mentioned in Section 4.1, is that any errors in the early states of alignment are later compounded. Some gauges were made to help with the alignment. These were useful, and should be in-

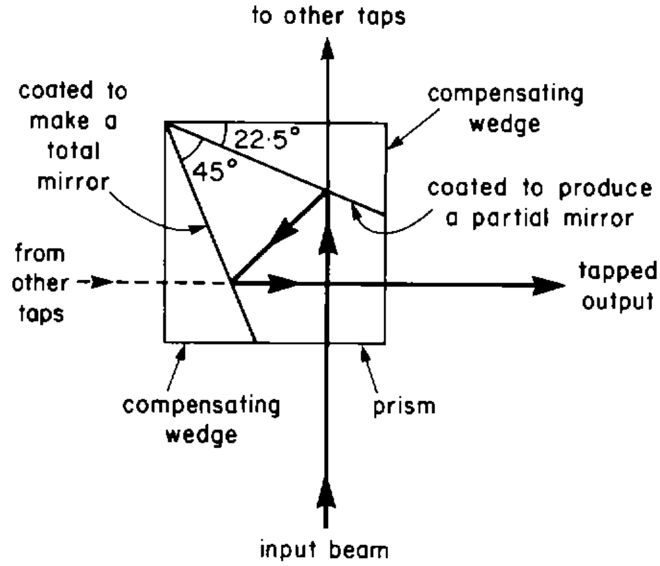

Fig. 5 – An alternative tap using a prism.

corporated into the design of any future matrix. It may also be possible to reduce the number of adjustments. For example, the lateral positions for the input and output ports need only be accurate to 0.1 mm and could be fixed.

In a fully-reflecting tap the mirrors could be replaced by a pentagonal prism. This has the advantage that prisms can be mass produced to a very high accuracy (angles between the faces accurate to within 5 minutes of arc), thus eliminating the need for adjustments at the tap. However, prisms are more expensive than mirrors. A prism version of the partially-reflecting tap is possible. It would be based on a prism with its faces coated with partially, fully and anti-reflecting coatings as shown in Fig. 5, corresponding to the two mirrors of the present design. The compensating prisms are needed to correct for refraction of the beams.

6. Maximum matrix size

One of the purposes of building the matrix was to attempt to predict the size of the largest matrix that could be constructed using this technique. The maximum size depends on the insertion loss that can be accepted, probably 25–30 dB in a television studio centre. Based on measurements of the 1-by-10 array this would put the limit at about 30-by-30. A matrix of this size would have a total insertion loss of about 27 dB, (a division loss of 15 dB and an excess loss of 12 dB).

The total loss in a 100-by-100 matrix would be too much, about 50 dB. However an array of this size could be built from sixteen 25-by-25 matrices interconnected via electro-optic repeaters. But

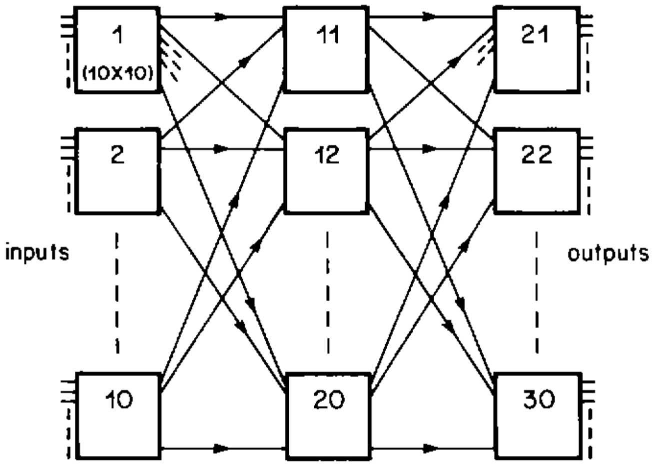

Fig. 6 – Possible 100 channel routing network formed from 10-by-10 matrices.

because each repeater contains an expensive optical detector and source, and at least 300 would be needed, this would be more expensive than an electrical matrix with its electro-optic interfaces.

An alternative to regeneration could be to increase the power margin, with higher-powered lasers and more sensitive receivers. Coherent optical detection,[4] which gives sensitivities close to the theoretical maximum, cannot be used in a switched system unless single-mode fibre is used.

If some restriction on routes is acceptable, it is possible to cascade small matrices without regeneration. For example, Fig. 6 shows thirty 10-by-10 matrices connected to give 100-by-100 switching, with 7000 fewer crosspoints than a true 100-by-100 matrix. The optical signal passes though at most 30 crosspoints on any route, therefore losses may be small enough to avoid regeneration. There is the added advantage that a failure in one matrix would not disable the entire system.

To overcome the size limitation a network based on a combination of optical wavelength-division multiplexing and electrical time-division multiplexing is now being considered for large installations.[5]

7. Conclusions

An experimental optical switching matrix has been produced that is capable of routing signals carried by multimode optical fibre. The average path loss on a four-channel section of the matrix is 15.7 dB, and on a 1-by-10 section (including the longest path), 17.9 dB. These include division losses of 6 dB and 10 dB respectively. Cross-talk is less than -70 dB. Although a considerable effort was required to align the matrix initially, the performance has remained stable over a long period including accelerated operating tests estimated to be equivalent to about 15 years of use.

It is estimated that the largest matrix possible with this technique is about 30-by-30. This assumes that a total insertion loss of up to 27 dB would be acceptable. This size is probably not large enough for the bigger studio centres unless some restrictions on routing were allowed. (For large installations a system based on optical wavelength-division multiplexing is now being considered).

The mirror matrix is an effective solution to the problem of optical switching in a digital television studio routing system, but the limitation in size and prejudice against mechanical devices may reduce its potential application. Nevertheless its development has provided valuable experience of optical fibre transmission and related techniques.

8. References

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Appendix

Calculation of mirror reflectance

The mirror reflectances increase with distance from the inputs. This compensates for the diminishing power in the beams and ensures that it is equally divided between the outputs. If there were no losses

the reflectance K_n of the nth tap in a row of N taps would be:

$$K_n = \frac{1}{(N+1-n)} \qquad (1)$$

In practice the losses must be taken into account. For convenience the term transmittance is used in this appendix, where

transmittance $= 1 -$ loss.

If the transmittance per tap is α for the undeviated beam and β for the reflected beam, the reflectance at the first tap is:

$$K_1 = \frac{1}{\beta M} \qquad (2)$$

where M is the required power margin (as a linear ratio, not dB).

The reflectance at the remaining taps is:

$$K_n = \frac{K_1}{\alpha^{(n-1)} - \sum_{i=1}^{n-1} \alpha^i} \qquad (3)$$

Equation 3 can be re-arranged to enable the maximum size of matrix N_{max} to be found.

$$N_{max} = \frac{\log\{K_1 - \log[1 + \alpha(K_1 - 1)]\}}{\log(\alpha)} + 1 \qquad (4)$$

Fig. 7 shows the maximum matrix size as a function of α and β. It can be seen that losses through the partial mirrors have a greater effect than losses in the reflected path.

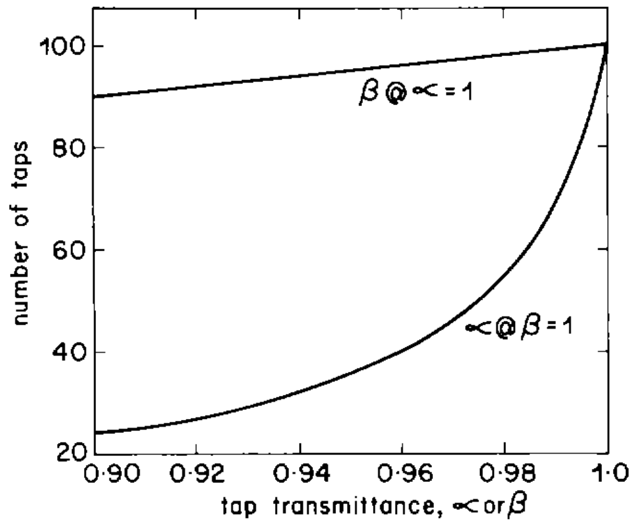

Fig. 7 – Maximum size of matrix against tap transmittance α for main beam and β for tapped beam.

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